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Measurements on One and Two Lines of Free-Flooded Magnetostrictive Ring Transducers

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CONTENTS

ABSTRACT

Magnetostrictive ring transducers are rugged and relatively insensitive to hydrostatic pressure when used in a free-flooded condition. Therefore, arrays of this type of transducer are ideally suited for deep submergence applications provided acoustic beam directionality is not required.

This report is concerned with measurements made on a single line of free-flooded, coaxially mounted magnetostrictive ring transducers and on two lines of meshed rings arranged to simulate segments of a biplanar array. The data presented shows the importance of spacing and arrangement of transducers in relation to the cancellation of generated acoustic pressures along selected array axes and provides information which will be useful in planning tests on a 30 ring biplanar array.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing.

AUTHORIZATION

NRL Problem S02-12

Project SF 101-03-18-8047

INTRODUCTION

Favorable hydrostatic pressure characteristics of free-flooded magnetostrictive ring transducers have revived interest in this type of transducer for current deep submergence applications. However, planar arrays of ring transducers do not have the directional characteristics usually specified for efficient, high power, search sonar systems. Acoustic directionality at relatively shallow depths may be achieved with the aid of pressure release material or reflectors. Both of these accessories, in common usage, are pressure sensitive and generally unsuitable for deep submergence. A probable solution, which would eliminate the need for cumbersome reflectors, is to use a suitable biplanar arrangement of ring transducers to achieve acoustic directionality. Theoretically, the acoustic energy radiated by the parallel planes of a biplanar transducer array reinforce each other in one direction and cancel in the opposite direction, providing the transducer elements are properly arranged, the planes are separated by a quarter wavelength distance (of a sound wave at the operating frequency), and then driven 90° out-of-phase.

MEASUREMENTS ON ONE AND TWO LINES OF FREE-FLOODED MAGNETOSTRICTIVE RING TRANSDUCERS

This report is concerned with exploratory measurements made at the NRL Transducer Calibration Platform at Lake Seneca on one and two lines of coaxially arranged magnetostrictive rings. The objectives were: 1) To determine whether free-flooded, ring shaped transducer elements arranged in two parallel coaxial lines and driven with variable-phase input voltages could be used to produce a directional acoustic beam with effective side lobe reduction. 2) To determine the effect of certain spacings and arrangements of transducer elements upon the scattering of acoustic energy and upon undesirable interactions between elements. 3) To obtain data that might be useful in planning measurements on a 30 ring, biplanar array.

The magnetostrictive rings used in the tests covered by this report were scroll wound from 0.005 inch thick cobalt-nickel strip consolidated with an epoxy resin and wound with a single layer of copper wire. Ring dimensions were as follows: inside diameter 5-3/8 inches, radial thickness 1/2 inch, and axial length 5/8". Figure 1 shows a single line of 12 rings in a coaxial arrangement. The rings were consecutively numbered from 1 to 12, starting from the left-hand side. The six odd numbered rings were electrically connected in series to form one group of elements, and the six even numbered rings were similarly connected to form the other group. These two groups of meshed rings were then used in various combinations to obtain all the data presented below.

A discussion of array orientation during measurements should be helpful in understanding the transmitting current response curves and beam patterns to be presented. Beam pattern measurements for the magnetostrictive ring array were made in two planes. The relationship between array orientation and the beam patterns obtained may be clarified by reference to Fig. 1. The array supporting frame, which was constructed of free-flooding pipe, has two attachment fittings labeled "A" and "B". When fitting "A" is attached to the vertical shaft which is used for lowering and rotating the array, the axis of the magnetostrictive rings is parallel to the surface of the water (as shown) and the beam pattern is conventionally labeled vertical. When fitting "B" is attached to the vertical lowering shaft, the ring axis is perpendicular to the surface of the water and the beam pattern is labeled horizontal. The 90° - 270° axis sketched on the photograph is parallel to the ring axis and the 0° - 180° axis is perpendicular to the ring axis as well as the plane of the array frame. When the receiving hydrophone labeled "H" and the array are aligned for the

0° beam pattern position, the 0° line <u>extended</u> passes through the center of the hydrophone. A study of Fig. 1 indicates that the 0° - 180° axis is common to both the vertical and horizontal beam patterns. However, when the "B" fitting on the frame is rotated 90° counterclockwise and attached to the vertical shaft in preparation for horizontal beam pattern measurements, the 90° - 270° axis of Fig. 1 must be rotated 90° clockwise if the degree markings on Fig. 1 are to match those on the horizontal beam pattern. Array orientation during all of the transmitting current response measurements was the same as the orientation for the zero position on the vertical beam patterns, that is, the array was suspended by frame fitting "A" (Fig. 1) and the receiving hydrophone was on the 0° line.

Measurements were first made on each group of six rings in the arrangement shown in Fig. 1 to determine if the operating characteristics of each group were similar. This is an important factor in obtaining good directionality in phased parallel-line arrays. As an example, if the resonant frequencies of two groups of transducers are considerably different, the electrical impedances may change very rapidly and at different rates for a given frequency in the resonant range. Thus, a given phase difference between the acoustic outputs of the two groups of transducers could not be maintained by a given phase setting between the input voltages to the transducers, and the directionality of the resulting acoustic beam would be adversely affected.

The transmitting current response curves of Fig. 2 were taken separately for each group of 6 series connected rings while the other group was passive. Arrangement of rings and the resonant frequency of each in air is shown in the right-hand sketch on the graph. Separation distance between rings was 1 inch. The response curves were taken along a line perpendicular to the axis of the rings and passing through center of the group of rings. Although both curves are similar, there is a response difference of approximately 1 db between the two curves. Peak transmitting current response at 7330 cps is 91 db vs 1 μbar per ampere at 1 meter for the upper curve and 89.8 db for the lower curve. Curves for input current "I" to the two groups of rings and input voltage "V" were transcribed from the original charts and show the true db variation without complicating the graph with additional db scales. Maximum input current variations for each group of rings are approximately 10 db while the input voltage curves are essentially constant. The current curves indicate that the electrical impedances at the input terminals for the two groups of rings are similar since the impedances vary inversely as the input current curves. Both impedances peak at approximately

7650 cps and dip at 8100 cps, that is, the resonant frequencies are essentially the same for both groups of transducers.

A vertical beam pattern taken at 7330 cps for the 6 even numbered rings in the group of 12 is shown in Fig. 3. The principal acoustic beam lies along the 0° - 180° axis and subtends a double angle, 2θ, of 31° at the 10 db down points. The 90° - 270° line on the beam pattern corresponds to the open ends of the line of rings (Fig. 1) and the pattern indicates that the acoustic pressure in this area is 25 db down. The vertical beam pattern for the 6 odd numbered rings is the same as Fig. 3. Horizontal beam patterns, taken around the periphery of the rings, are circular for both groups of rings and are not shown. The above data indicates that the operating characteristics of both groups of rings are essentially the same when they are arranged as described above.

When all twelve of the coaxially arranged rings (with a 1" separation between rings) were driven in phase, the transmitting current response in the direction 0° - 180° (Fig. 1) increased to 97.1 db as shown in Fig. 4. Maximum variations in the input voltage and current curves are 1/2 and 3 db, respectively; therefore, the electrical impedance variation, as determined from these curves, is much less than it is for each group of 6 rings as shown by the curves of Fig. 2. Fig. 5 shows a vertical beam pattern taken at 7900 cps for the 12 coaxial rings driven in phase. The acoustic pressure at the open ends of the rings (90° - 270°) is 20 db down from peak response. This pattern as well as other patterns taken at frequencies corresponding to points along the peak of the transmitting current response curve were similar to the beam pattern for 6 coaxial rings but 5 db higher along the 90° - 270° axis.

The transmitting current response curve in Fig. 6 was obtained when 6 even numbered rings of the 12 coaxially arranged rings were driven 180° out-of-phase with the 6 odd numbered rings. Peak transmitting current response was 71 db vs 1 μbar/ampere at 1 meter. Therefore, the transmitting current response difference between in-phase (Fig. 4) and out-of-phase (Fig. 6) driving of two groups of coaxially arranged rings is 26.1 db, or really 30 db, if the saddle part of the response curve in Fig. 6 is considered. The mechanical Q in water for the arrangement given in Fig. 6 is 3.6 if frequencies at the 3 db down points from the 30 db value are used. Both the input current and voltage curves of Fig. 6 show the large and steep variations associated with significant cancellation of acoustic energy. Phase relationships between the mechanical velocities of the radiating surfaces of the two groups of rings were not obtained during these tests because of the lack of accelerometers suitable for attachment to the rings.

The following several measurements were made in order to determine whether an equally good cancellation of acoustic pressure could be obtained along a selected axis for two parallel lines of rings separated by a half-wavelength distance (at a given frequency) and driven in phase. In this arrangement, the even numbered rings in the original line array were withdrawn (as shown in Fig. 7) until the ring axes of the two lines of meshed rings were 1/2 wavelength apart at the resonant frequency (7880~) for the arrangement. The axial distance of 1" between rings was maintained. Referring to Fig. 7, the axes sketched on the array frame supports "A" and "B" correspond respectively to the axes on the vertical and horizontal beam patterns and are the same as the axes for Fig. 1 but are sketched on the frame supports instead of through the center of the array to avoid confusion. As in Fig. 1, transmitting current response measurements were made with the receiving hydrophone on the 0° - 180° axis. In this direction the ring arrangement of Fig. 7 appears as a <u>2 line planar array</u> and the transmitting current response is a maximum. If the beam patterns are obtained at a frequency corresponding to peak response on the transmitting current response curve, then both the vertical and horizontal beam patterns will also show maximum response along the 0° - 180° axis which is common to both patterns (see Fig. 7). Cancellation of acoustic pressure will be indicated in the horizontal beam pattern along the 90° - 270° axis. Fig. 7 shows that this axis (sketched on suspension fitting "B") lies in a plane containing the parallel axes of the two groups of rings.

Fig. 8 shows a transmitting current response curve for the magnetostrictive ring arrangement shown in Fig. 7 and described above. The peak transmitting current response at 7880 cps was 95.1 db vs 1 μbar per ampere at 1 meter or 2 db less than for the two groups of rings arranged in a single line and driven in phase. Mechanical Q as determined from the response curve was 9.7. The input current curves on the graph are similar to the curves of Fig. 2 but the transmitting current response curve has a single instead of the double peaks previously noted. The vertical beam pattern (Fig. 9) taken at 7880 cps shows a principal beam width of 34° at the 10 db down points and a 24 db drop in acoustic pressure near the open ends of the rings or along the 90° - 270° line on the pattern. The horizontal beam pattern of Fig. 10 was taken at 7880 cps and shows both the maximum pressure along the 0° - 180° axis and the reduction in pressure due to cancellation along the 90° - 270° axis. Orientation and separation of the two parallel lines of rings is sketched at the center of the pattern to indicate the axis (90° - 270°) along which cancellation of acoustic pressure occurs when the two groups of rings are driven in phase. The acoustic pressure along the cancellation axis is 15 db down from maximum pressure for this arrangement. When the same two groups of rings with the same axial spacing between rings were arranged in a single line as described under the first part of the measurements, the acoustic pressure cancellation between the two groups of rings was 30 db down between the in-phase and out-of-phase driving. In both cases, the rings were arranged and phased to cancel the generated acoustic pressure in specified directions. The considerable change in the acoustic pressure cancellation capability of the two groups of rings as used in the two parallel lines may be attributed to a change in the acoustic interaction pattern due to that particular arrangement.

An attempt was made to increase the acoustic pressure cancellation between the two lines of rings separated by a half-wavelength distance by varying the axial separation distance between rings. Fig. 11 shows a transmitting current response curve for an axial separation of 1/2" between rings. The peak response is 91.6 db vs 1 μbar per ampere at 1 meter or 3.5 db lower than for the 1" separation between rings. The principal and secondary lobes in the vertical beam pattern of Fig. 12 are considerably broader than those of Fig. 9, however, the acoustic pressure near the open ends of the rings is 36 db down compared to 24 db down for Fig. 9. A horizontal beam pattern for the arrangement is shown in Fig. 13. The 90° - 270° line on the pattern is the cancellation axis or the line along which the axes of the two lines of rings are separated by a half-wavelength distance (see Fig. 7). Acoustic pressure in this region is 21 db down or 6 db better than for the previous axial separation distance between rings. When the axial separation distance between rings was increased above the original 1" setting to 1-1/2", the transmitting current response as indicated by the curve of Fig. 14 increased to 93.5 db or 1.9 db above the last measured value and the curve again assumed the single peak shape observed for the 1" axial separation. A vertical beam pattern taken at the peak response frequency of 7758 cps is shown in Fig. 15. The principal lobe is 27° wide at the 10 db down points and the acoustic pressure at the open ends of the rings (90° - 270° line) is 30 db down. The horizontal beam pattern of Fig. 16 indicates that the acoustic pressure along the cancellation axis (90° - 270°) is 18 db down. Thus, the last three sets of measurements have shown that cancellation of acoustic pressure in two line arrays depends, to a certain extent, on the axial separation of ring transducer elements in the lines.

For the final series of measurements the two parallel lines of free-flooded magnetostrictive ring transducers of Fig. 7

were separated by a quarter-wavelength distance at the resonant frequency for the arrangement, and driven 90° out-of-phase to effect a reinforcement of acoustic pressure in one direction and a cancellation of acoustic pressure in the opposite direction. This is the spacing and phasing that would be appropriate between two planes of a directional biplanar array consisting of many ring transducers. The purpose of the preceding measurements was, in part, to determine the pressure cancellation capability of two groups of ring transducers under different spacing and phasing conditions not applicable to directional biplanar arrays, and to compare these measurement results to those given below.

Since the quarter-wavelength separation distance (1.9" at 7340 cps) between the two lines of rings shown in Fig. 7 is along the 90° - 270° axis sketched on suspension fitting "B", the directional properties of the two lines of rings will be indicated on the horizontal beam pattern. As in all the other <u>transmitting current response</u> measurements, the hydrophone was on the 0° - 180° axis of Fig. 7, perpendicular to the plane through the ring axes, and 5 meters away. Submergence depth, as in previous measurements, was 75 feet. Fig. 17 shows the transmitting current response curve taken when the phase difference between input voltages to the two lines of rings was set at 90° and the frequency was varied from 6000 to 9000 cps. The peak response at 7340 cps was 90.2 db vs 1 μbar per ampere at 1 meter. Input voltages to both lines of rings remained essentially constant throughout the frequency range used. The impedance (and phase) changes associated with resonance in each of the two lines of rings occurred at frequencies separated by approximately 250 cps as indicated by the dips in the current curves. Therefore, the acoustic loading due to this particular arrangement was such that a constant phase difference between the velocities of the two groups of rings was not maintained near resonance. Thus a fixed phase difference between input voltages to the two groups of rings would not produce optimum cancellation of acoustic energy in a given direction. Fig. 18 shows the vertical beam pattern for the arrangement. The reason for the dissymmetry between the upper and lower half of the pattern is not known. Patterns taken over a frequency range extending from 7000 to 8000 cps were of this general shape. The acoustic pressure near the open ends of the rings (90° - 270° axis) was 21 db down from the pressure at 0°.

The horizontal beam pattern in Fig. 19 was plotted with the control attenuator set 15 db lower than the setting for the previous vertical pattern in order to accommodate the beam pattern elongation along the 90° - 270° axis. The cross sectional sketch of the two lines of rings at the center of the pattern shows that the parallel axes of the rings are a quarter-wavelength apart along the 90° - 270° line. Therefore, cancellation and reinforcement of acoustic pressure occurs in opposite directions along this line when the two groups of rings are driven 90° out-of-phase. The pattern indicates that the difference between the maximum and minimum pressures on the directional axis (90° - 270°) was just 7 db. Efforts were made to compensate for possible errors in the quarter-wavelength separation distance by adjusting the phase difference between the input voltages to the two lines to values less and greater than 90°. No appreciable improvement in acoustic directionality was noted for these phase shifts. Figs. 20, 21, and 22 are curves and beam patterns obtained when the input voltages were 110° out-of-phase and are shown for comparison purposes.

Values calculated for the directivity indices of the beam patterns obtained for the various two parallel line arrangements were rough approximations because the patterns were taken only in the horizontal and vertical planes and the acoustic beam volume was assumed to be equal to the volume generated by drawing curved lines between corresponding points on the contours of the two perpendicularly disposed beam patterns. Therefore, the efficiencies were also approximate values that varied from 40% for the single line of ring elements driven in-phase, to 13% for the two parallel lines of meshed rings separated by a quarter-wavelength distance and driven 90° out-of-phase.

SUMMARY

Exploratory measurements were made on two groups of free-flooded magnetostrictive ring transducers, which were coaxially arranged to form two lines of 6 rings each. The two lines were then used in a number of different combinations to show that the acoustic pressure cancellation capability, between lines of ring transducers having very similar operating characteristics, is a function of ring and line arrangement or of acoustic reflections and interactions between the ring elements.

The data indicates that when 12 magnetostrictive rings were arranged in a single coaxial line of <u>even</u> and <u>odd</u> numbered rings, the difference in acoustic pressure generated around the periphery of the rings was 30 db for in-phase and out-of-phase operation of the even and odd groups of rings. This was the best measured value of cancellation of the real part of the radiation load for the arrangements tried. Axial separation distance between rings was one inch.

For the second part of the measurements, the even numbered rings in the single line were withdrawn to form two parallel lines of rings separated by a half-wavelength distance and driven in phase (to effect cancellation of acoustic pressure along the line of separation), the difference in acoustic

pressure measured along the 0° - 180° or maximum response axis (as shown in Fig. 2) and the 90° - 270° or cancellation axis was 15 db down, or 15 db less than for the preceding case. This indicates that the acoustic pressure cancellation capability of the two lines of rings was modified by rearranging the lines and thus changing the acoustic interaction pattern between them. An indication that some, and perhaps all, of the pressure cancellation capability could be restored was obtained by changing the spacing between the rings in each line. When the axial separation between the rings was decreased to 1/2 inch, the acoustic pressure along the cancellation axis changed to 21 db down, which is a 6 db improvement over the 1 inch separation. When the axial distance between rings was increased to 1-1/2 inches the acoustic pressure measured along the cancellation axis was 18 db down or a 3 db improvement over the value obtained at the initial setting. Optimum arrangement of rings for cancelling acoustic pressures along selected axes were not determined because of the limited time available at Lake Seneca for these tests.

For the final measurement of the series, the axial distance between rings was kept the same as in the preceding arrangement but the separation distance between the two parallel lines of meshed rings was changed from one-half to one quarter-wavelength (to simulate segments of a biplanar array). When the two lines of rings were driven 90° out-of-phase to produce a directional acoustic beam, the difference between the maximum and minimum acoustic pressures on the directional axis as shown in Fig. 19 was just 7 db. Data presented above suggests that an acceptable improvement in acoustic directionality might be obtained if the spacing and arrangement of rings is altered sufficiently to break up the acoustic interaction pattern of the present arrangement. Measurements planned on a 30 magnetostrictive ring biplanar array will provide an opportunity to try arrangements not possible with a small number of rings.

Beam patterns obtained in the above measurements show that the acoustic pressure in the region near the open ends of the rings (along the 90° - 270° axis in the vertical beam patterns) varied from approximately 20 to 36 db down from the broadside direction. This suggests planar or biplanar arrays of ring transducers in a wheel shaped pattern, that is, the axes of the lines of rings would lie along the imaginary spokes of a wheel. The resulting beam patterns would have very low acoustic pressures in the peripheral region of the spoke-like array and be conducive to the generation of sharper beam patterns.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the fine support and cooperation received from the people involved in these measurements. Mr. E. Tuck's assistance in helping with data taking and processing is greatly appreciated as is the cooperation of the members of the Lake Seneca Barge. Thanks are due to Mr. Gus Nordstrom for remodeling the rings and designing the frame for the array.

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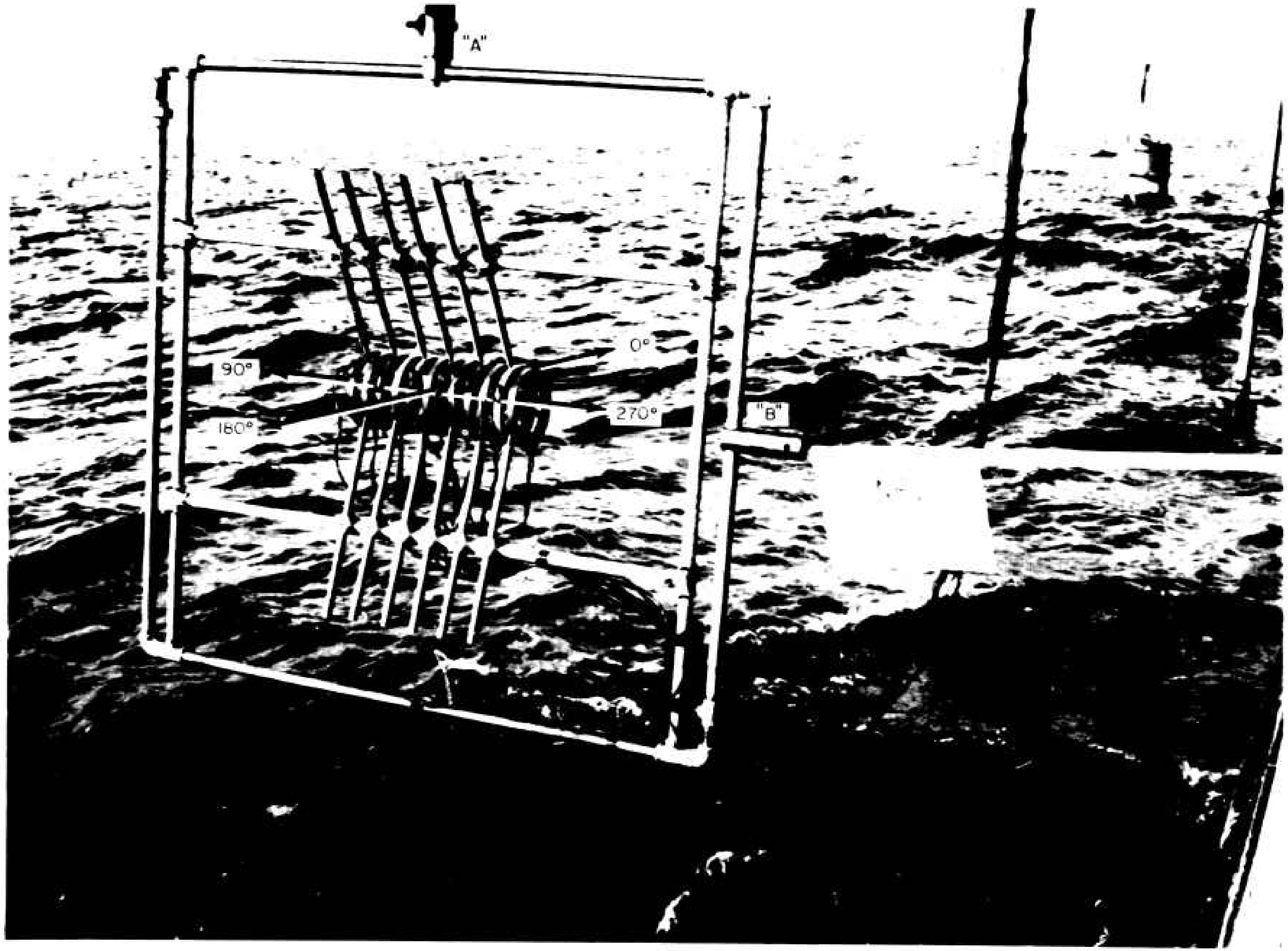

Figure 1

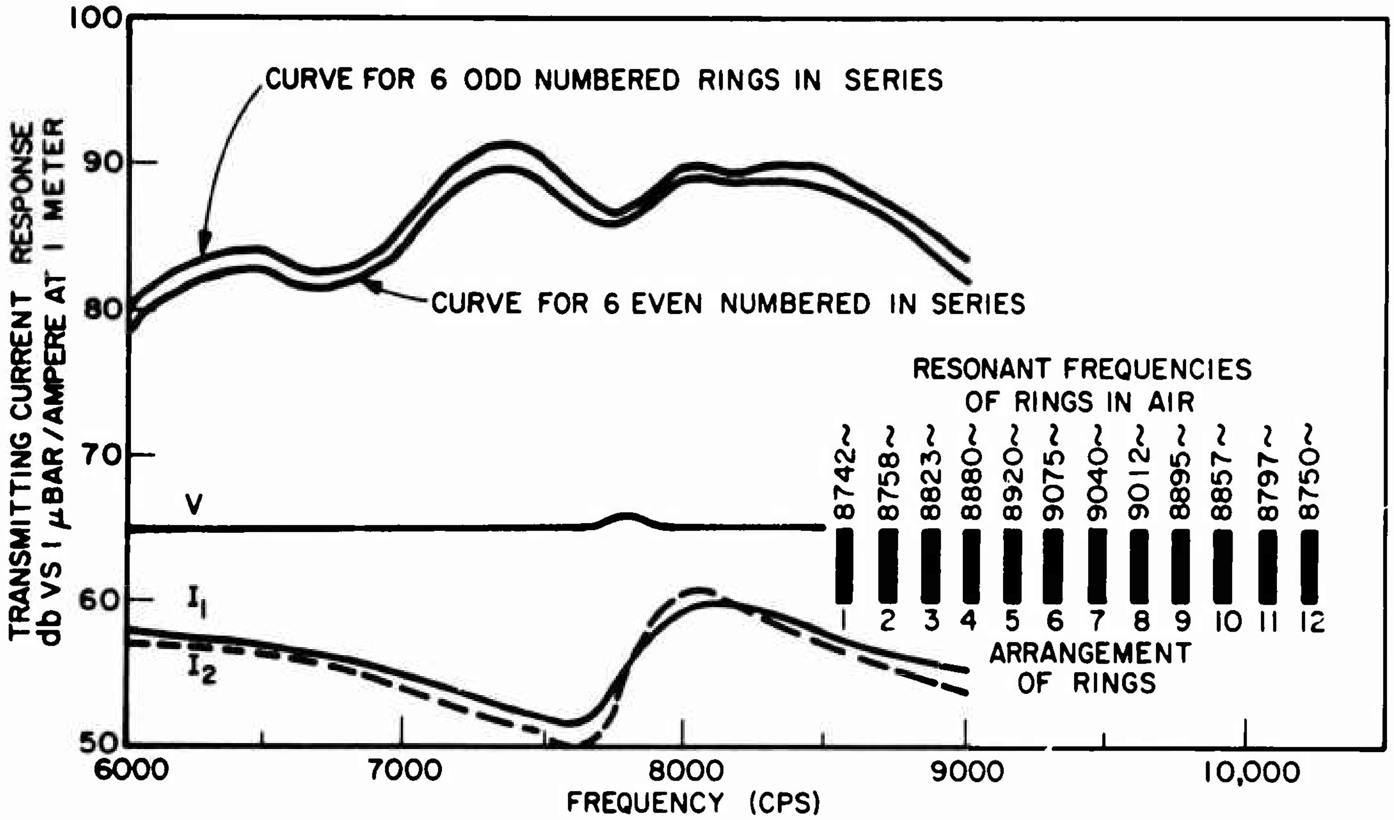

Fig. 2 - Transmitting current response curves
Single line of 12 coaxial rings
Distance between rings = 1.0 in.
Only 1 groun of 6 alternate rings driven at one time

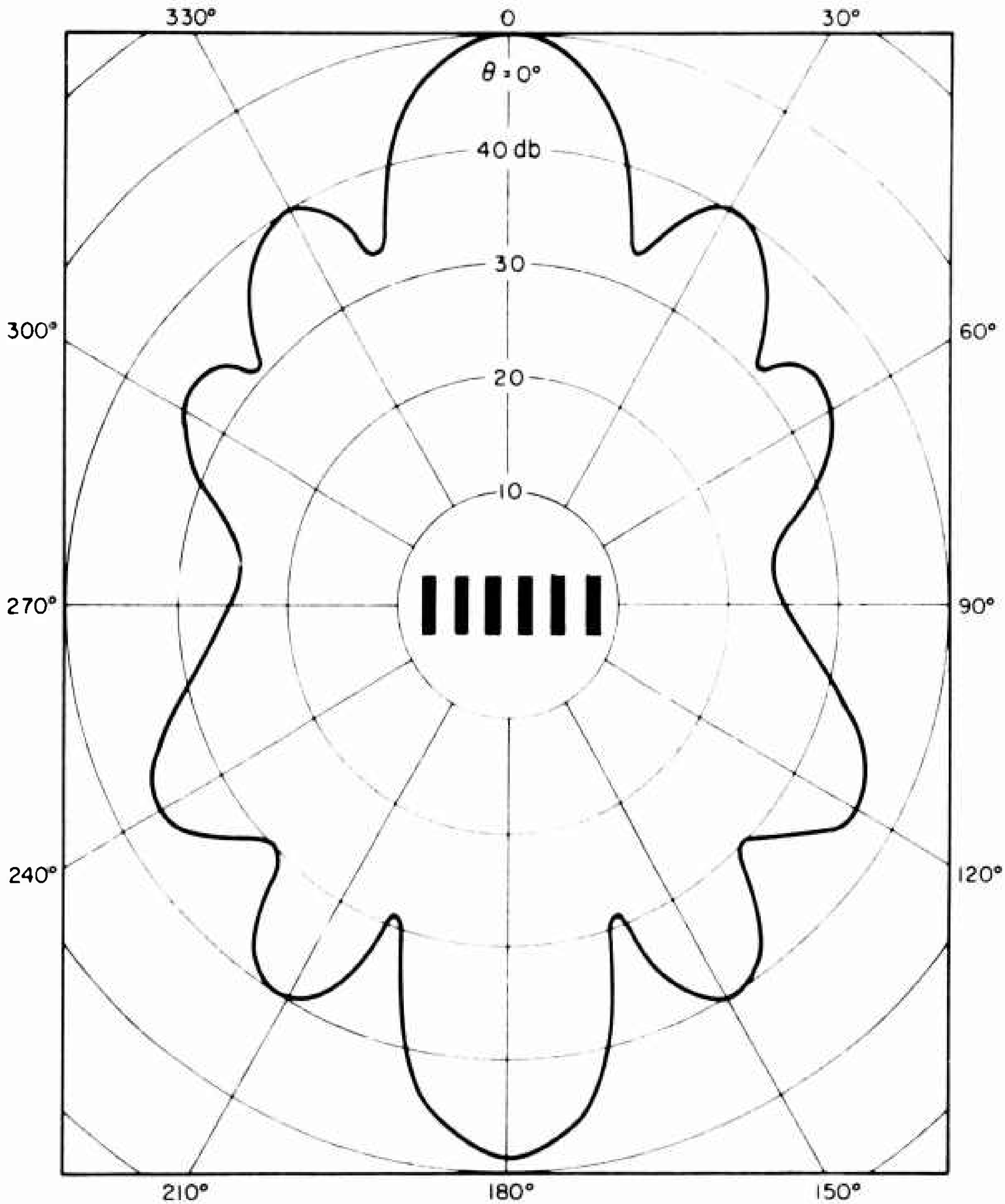

Fig. 3 - Vertical beam pattern for 6 even numbered rings of a coaxial line of 12 rings
Rings = 1 in. apart
f = 7330 cps

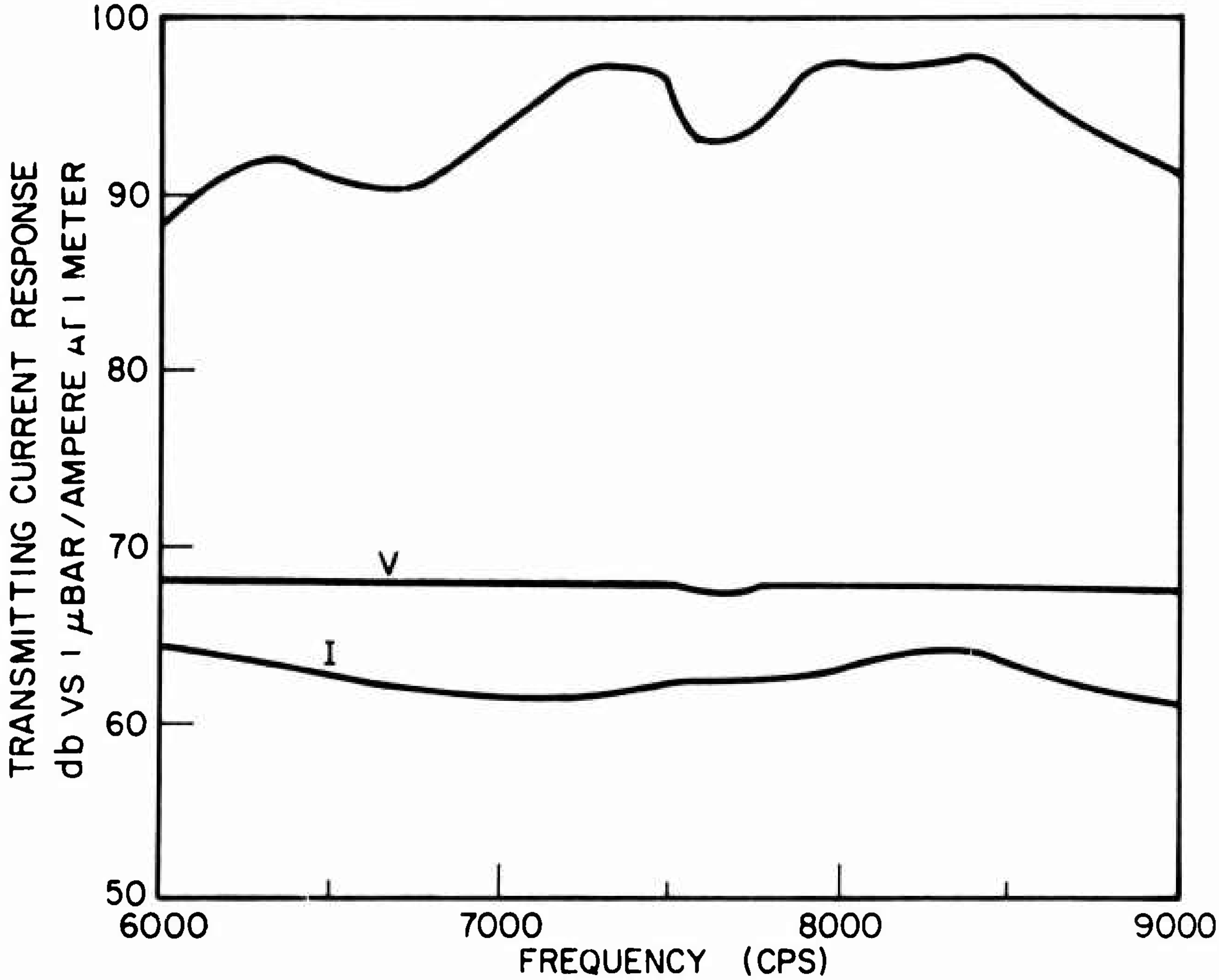

Fig. 4 - Transmitting current response curves
Single line of 12 coaxial rings
Distance between rings = 1.0 in.

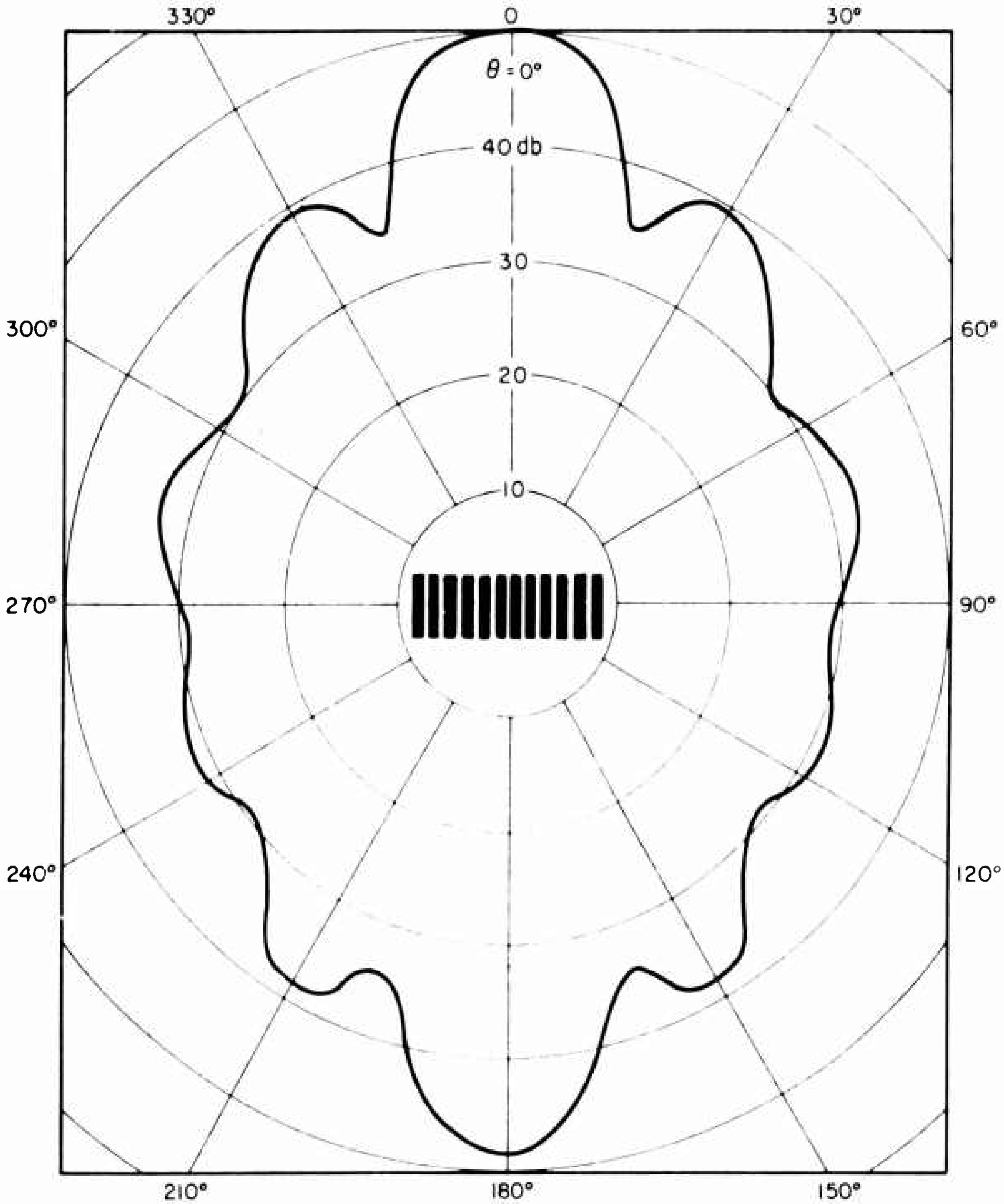

Fig. 5 - Vertical beam pattern for 12 coaxial rings
Rings = 1 in. apart
f = 7900 cps

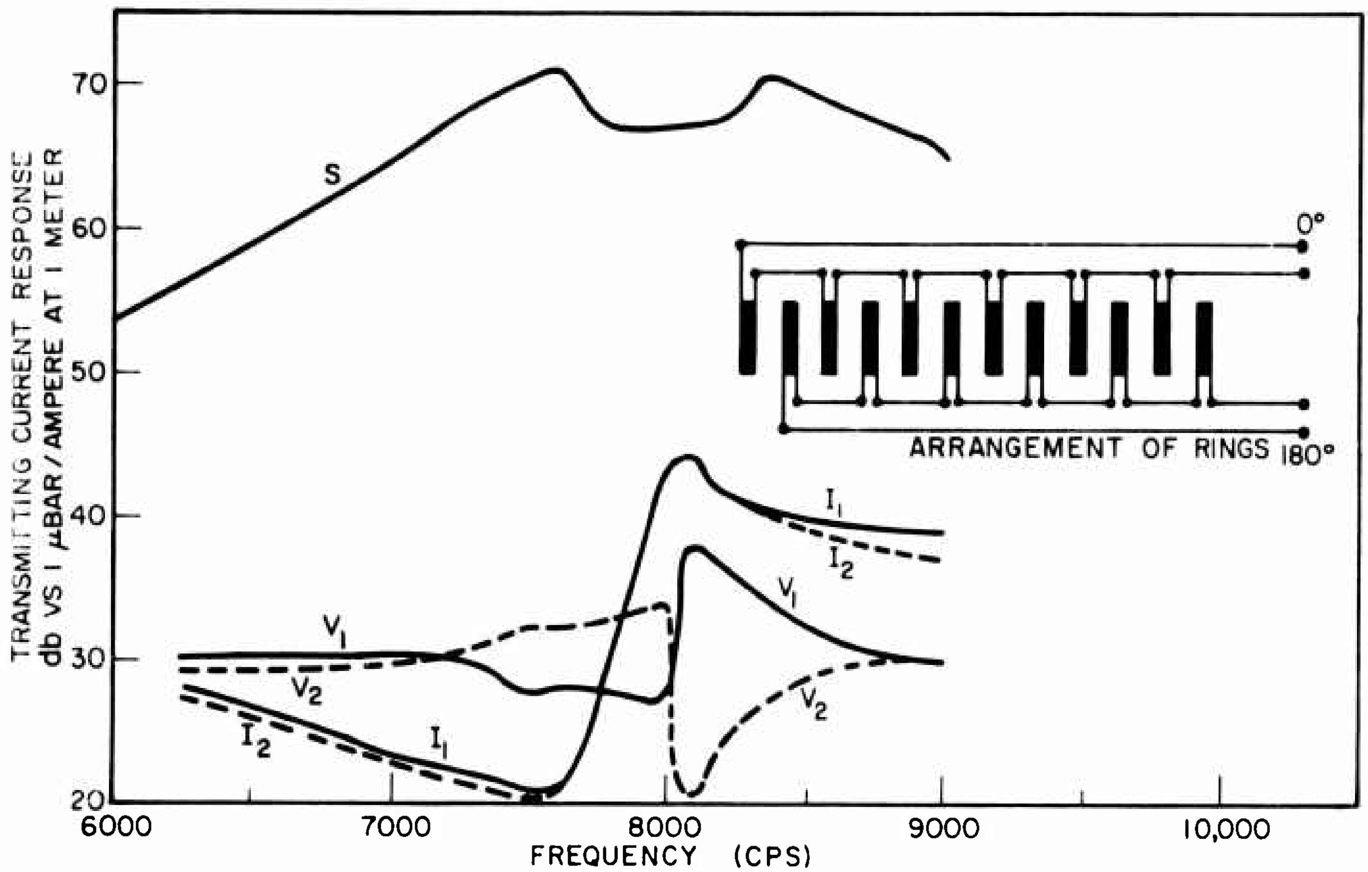

Fig. 6 - Transmitting current response curves
Single line array of 12 coaxial rings
Distance between rings = 1.0 in.
Input voltages to even and odd numbered rings are 180° out-of-phase

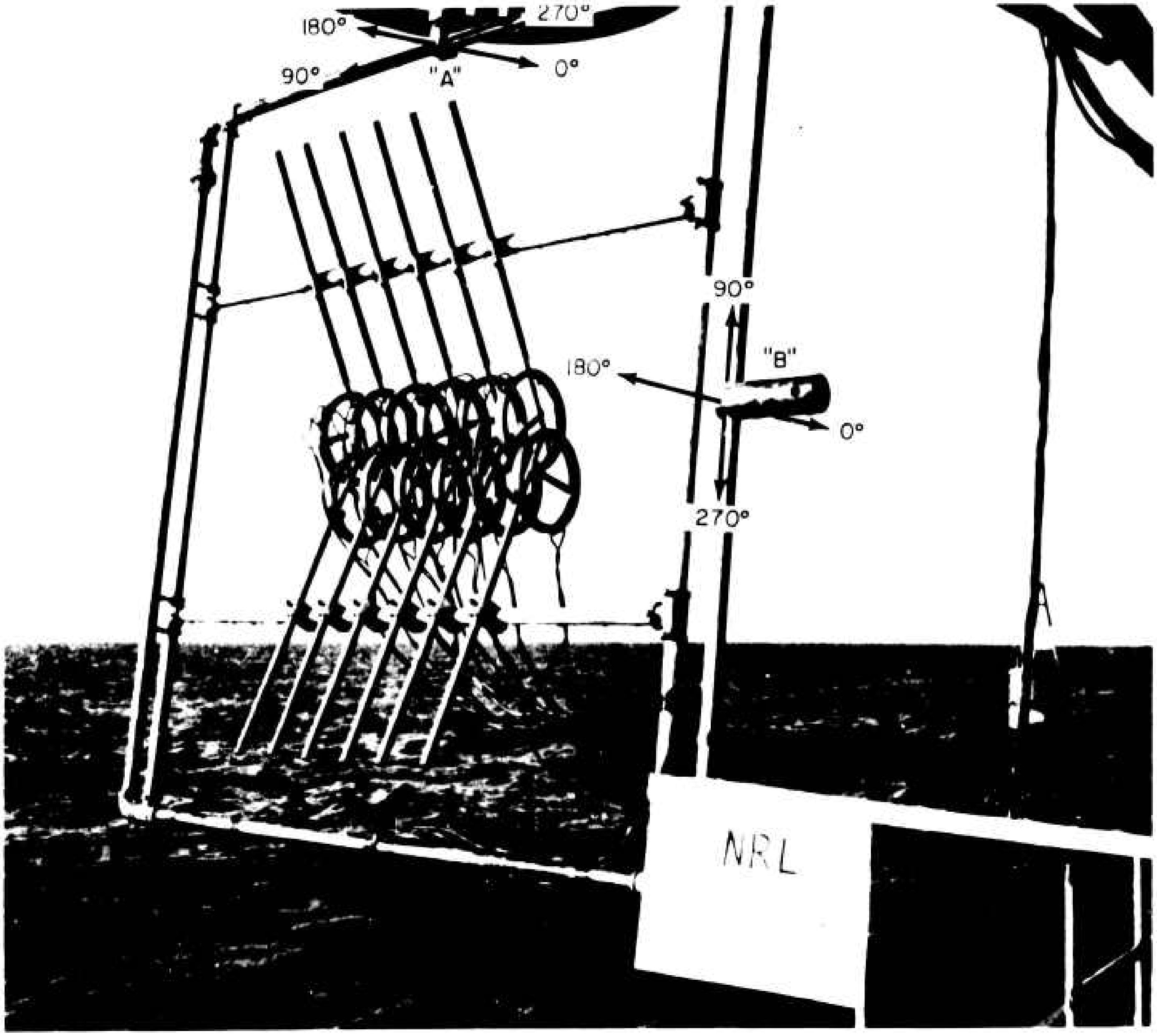

Figure 7

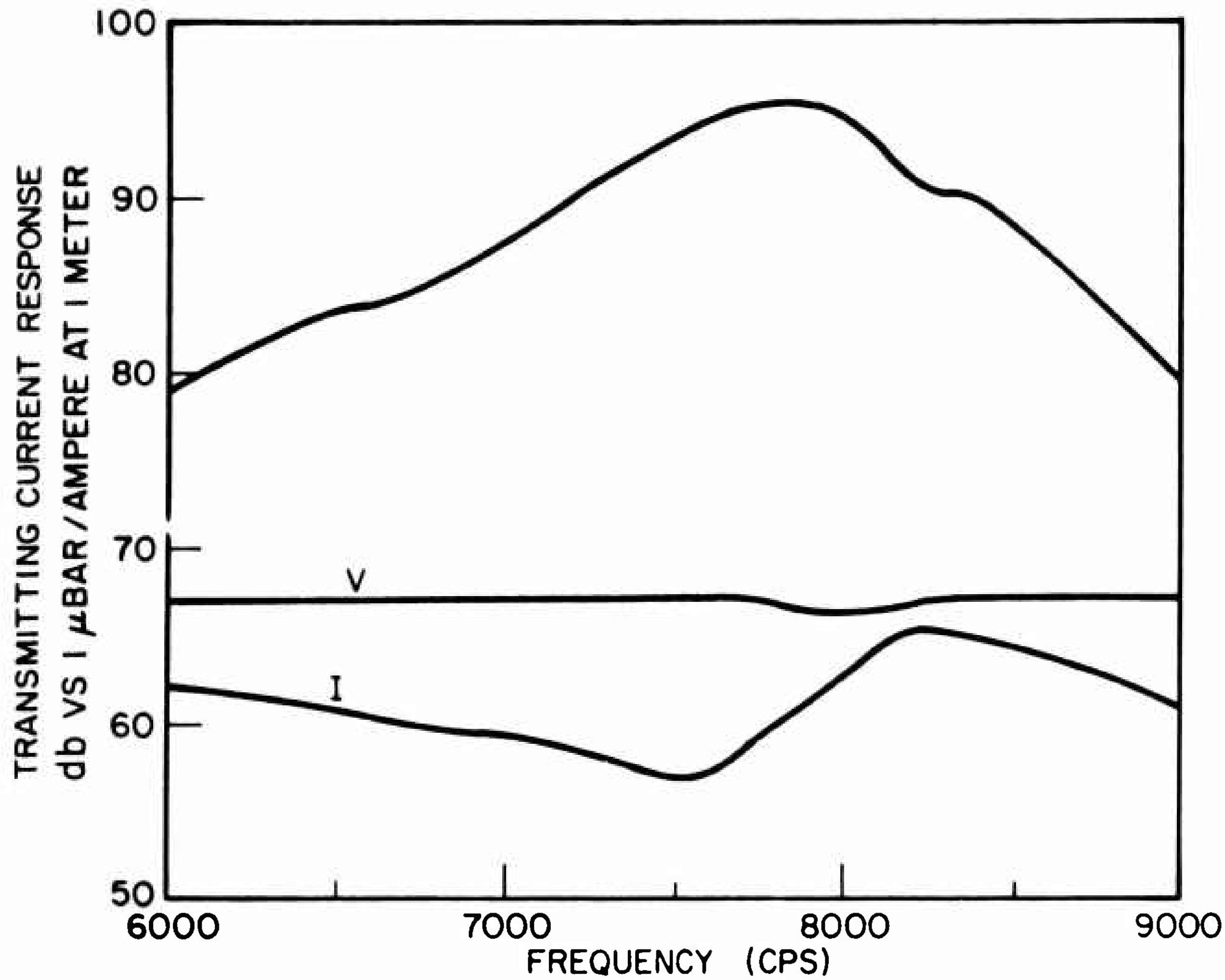

Fig. 8 = Transmitting current response
2 line array of magnetostrictive rings
6 series connected rings in each line
Both lines driven in phase
Rings = 1 in. apart
Ring axes = $\lambda/2$ apart

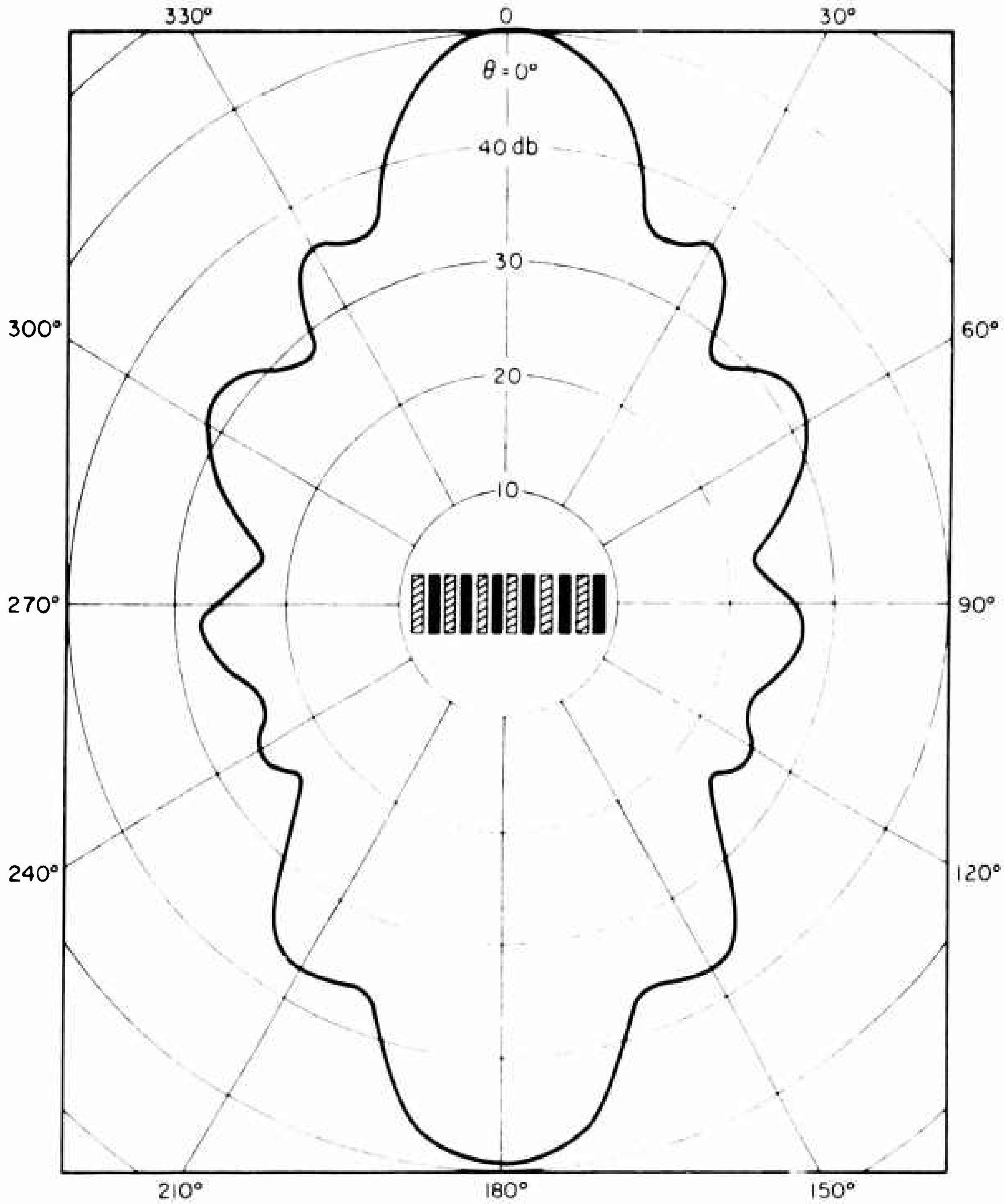

Fig. 9 - Vertical beam pattern
2 line array of rings
Lines driven in phase
Ring axes = $\lambda/2$ apart
Rings = 1 in. apart
f = 7880 cps

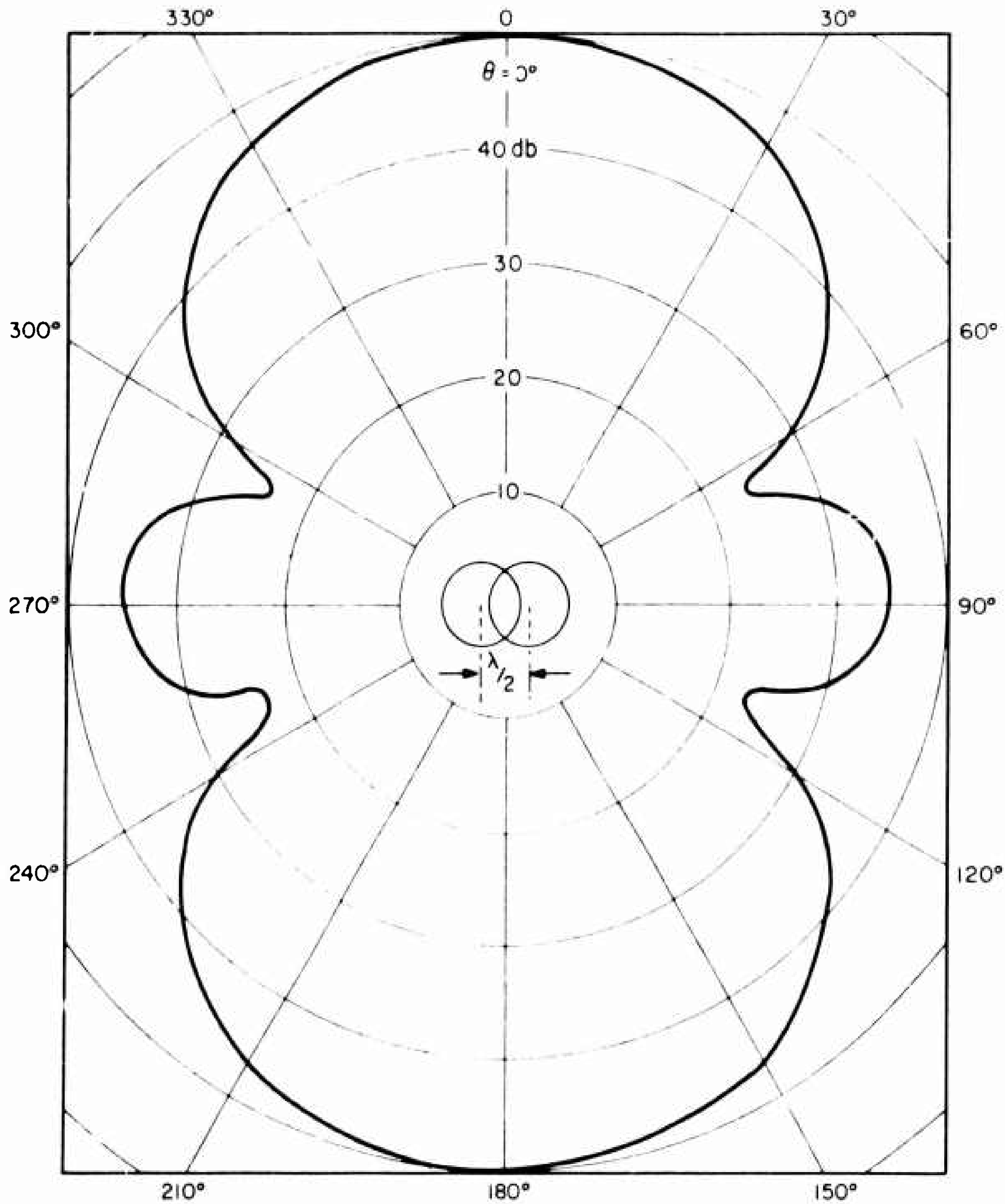

Fig. 10 - Vertical beam pattern for Fig. 9

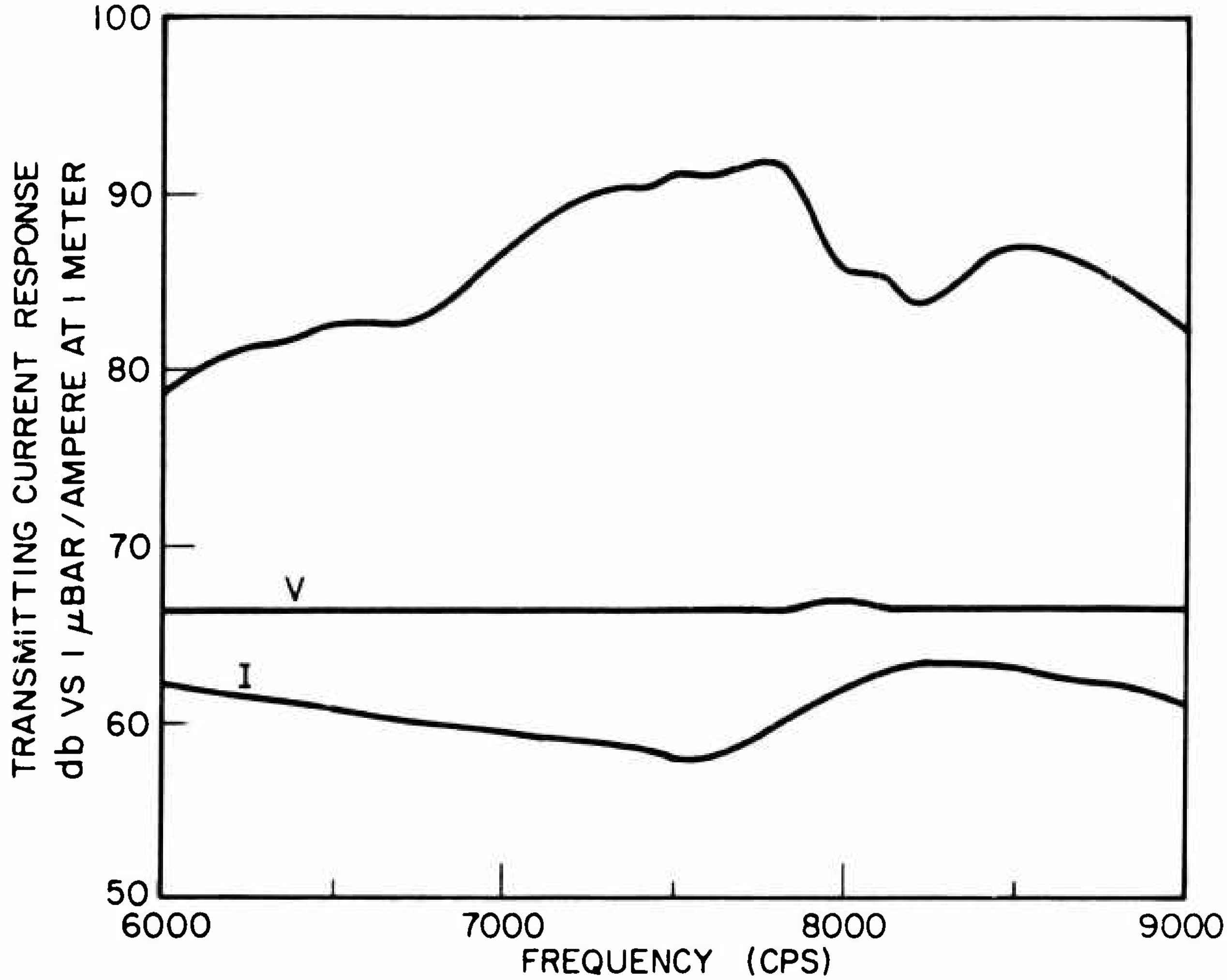

Fig. 11 - Transmitting current response
2 line array of magnetostrictive rings
6 series connected rings in each line
Both lines driven in phase
Rings = 1/2 in. apart
Ring axes = $\lambda/2$ apart

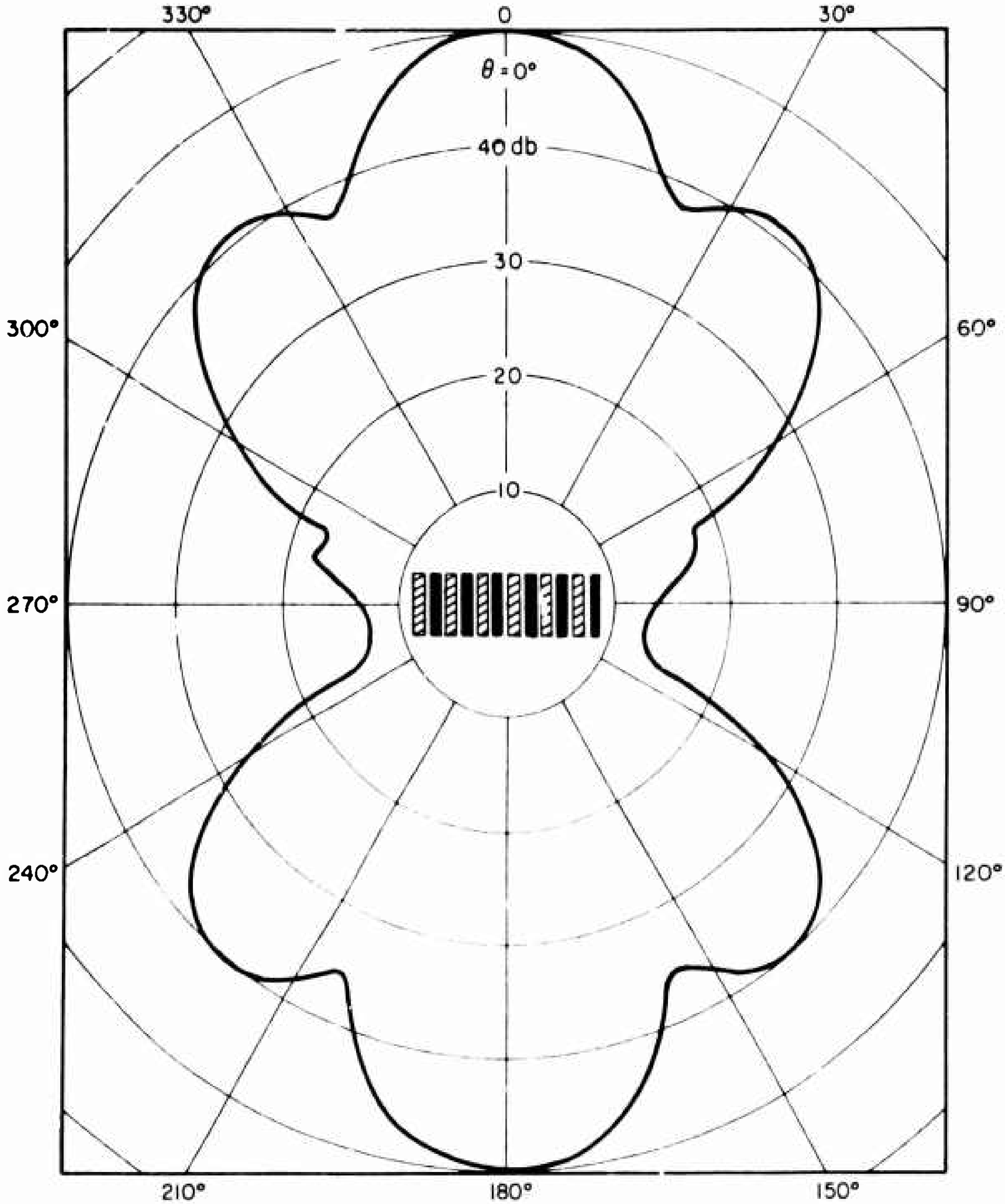

Fig. 12 - Vertical beam pattern
2 line array of rings
Lines driven in phase
Ring axes = $\lambda/2$ apart
Rings = 1/2 in. apart
f = 7600 cps

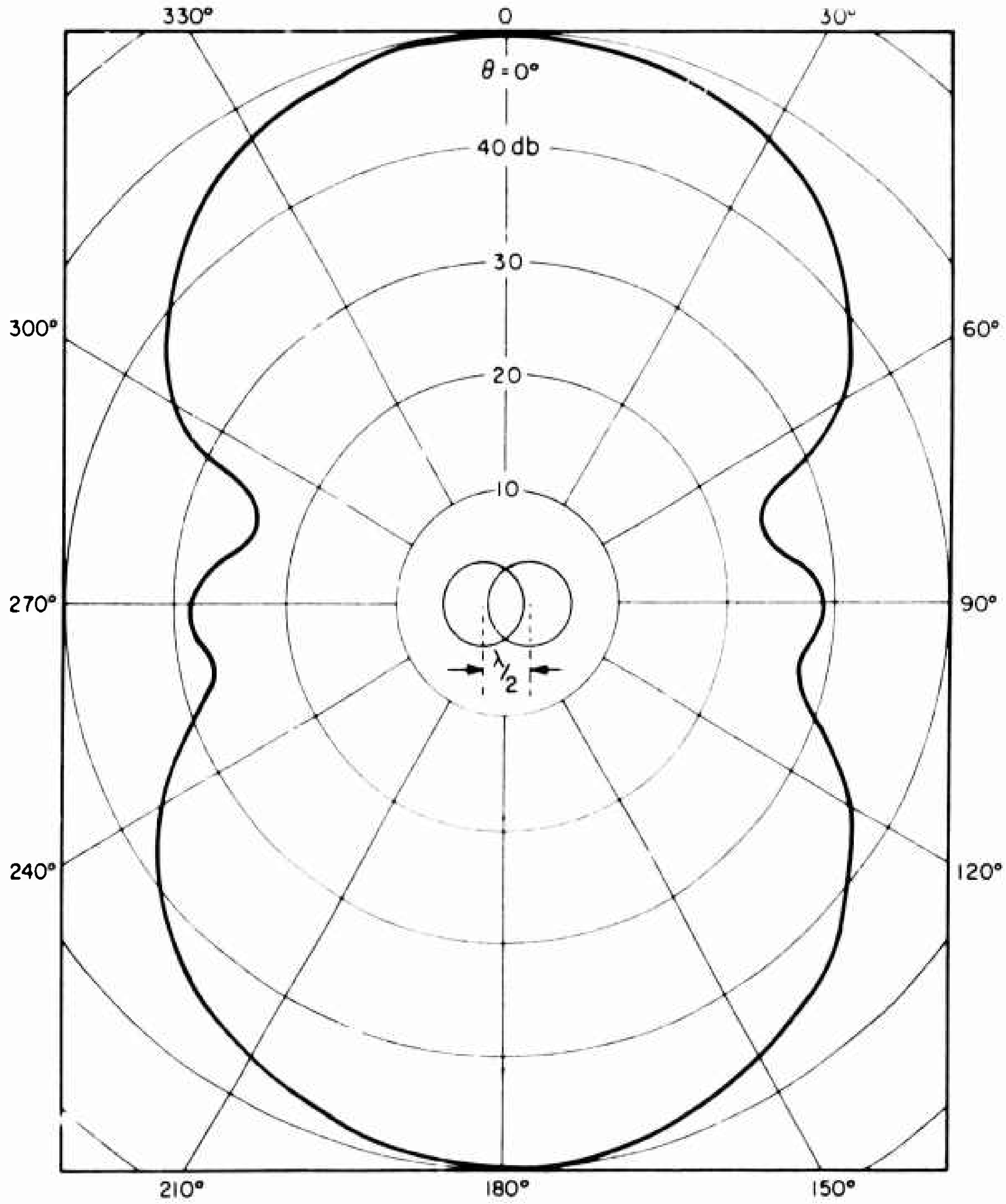

Fig. 13 - Horizontal beam pattern for Fig. 12

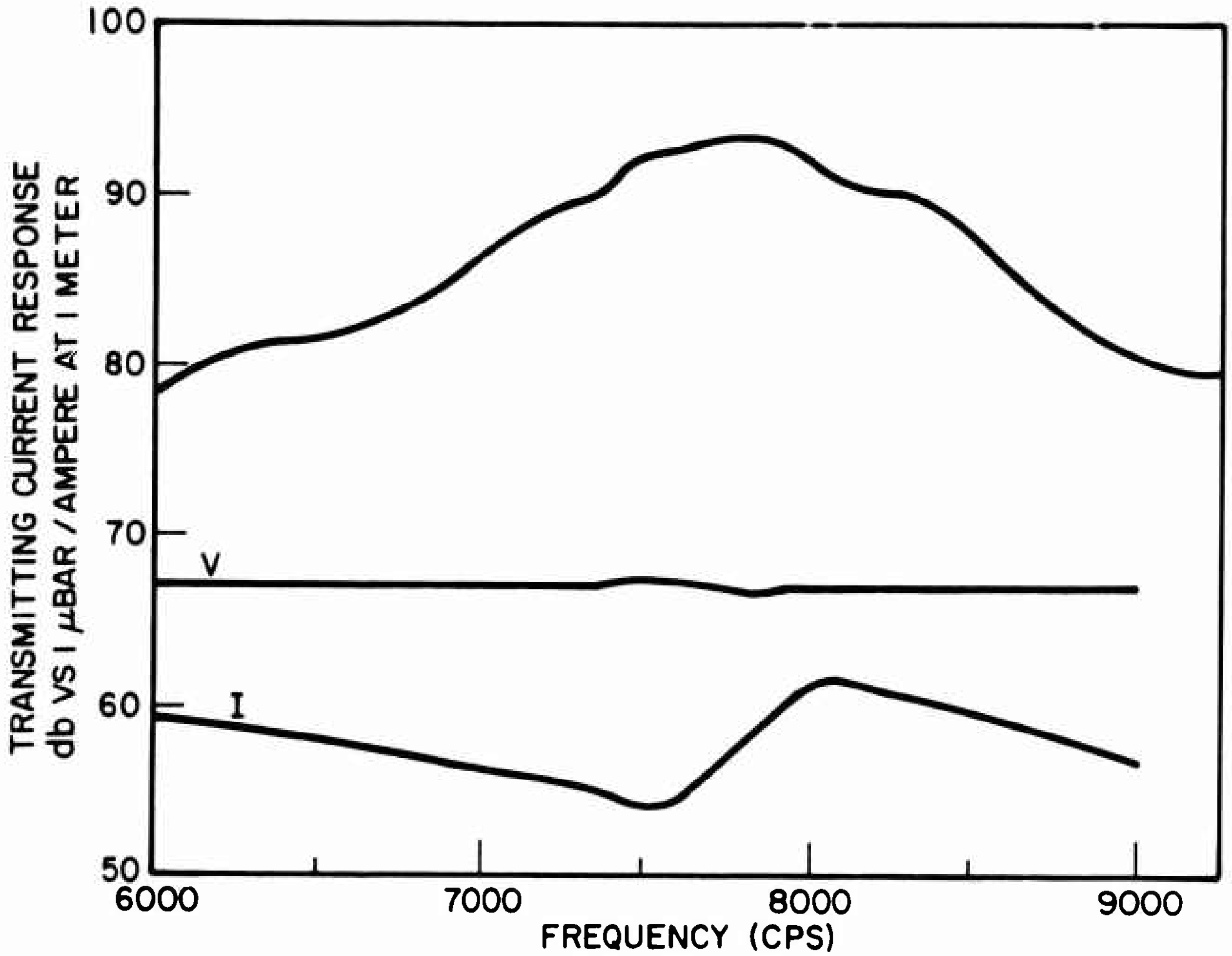

Fig. 14 - Transmitting current response
2 line array of magnetostrictive rings
6 series connected rings in each line
Both lines driven in phase
Rings = 1-1/2 in. apart
Ring axes = λ/2 apart

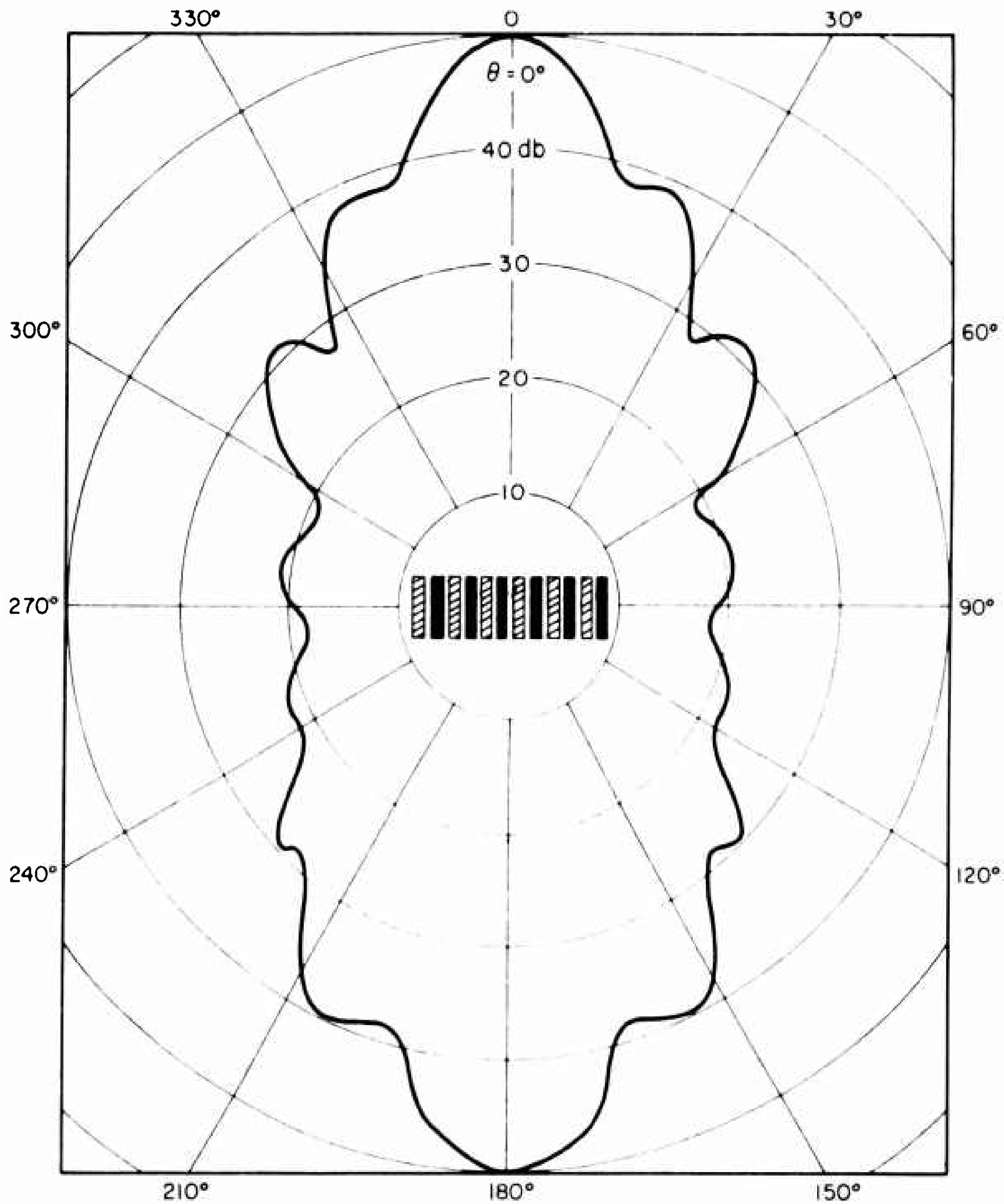

Fig. 15 - Vertical beam pattern
2 line array of rings
Lines driven in phase
Ring axes = λ/2 apart
Rings = 1-1/2 in. apart
f = 7758 cps

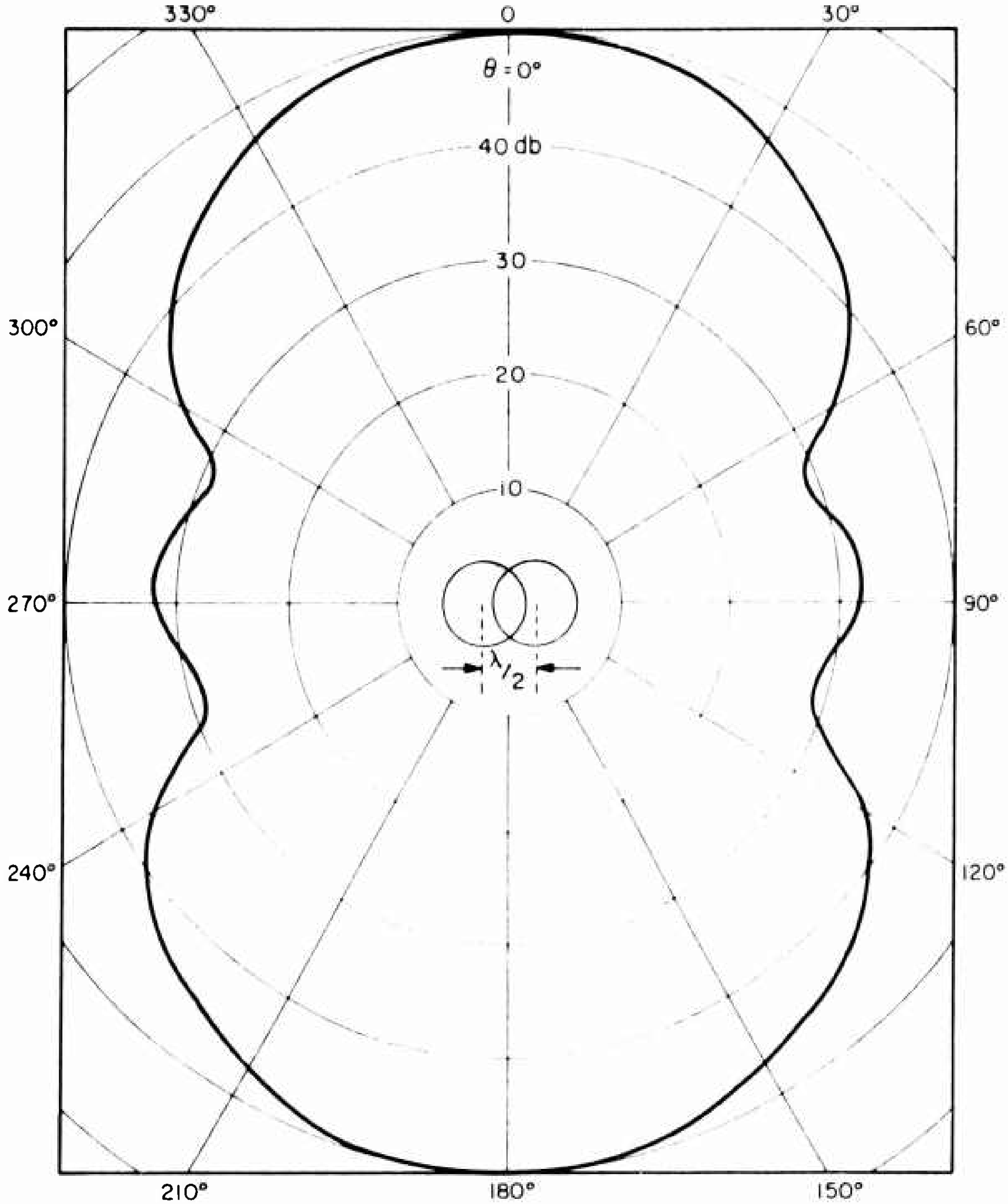

Fig. 16 - Horizontal beam pattern for Fig. 15

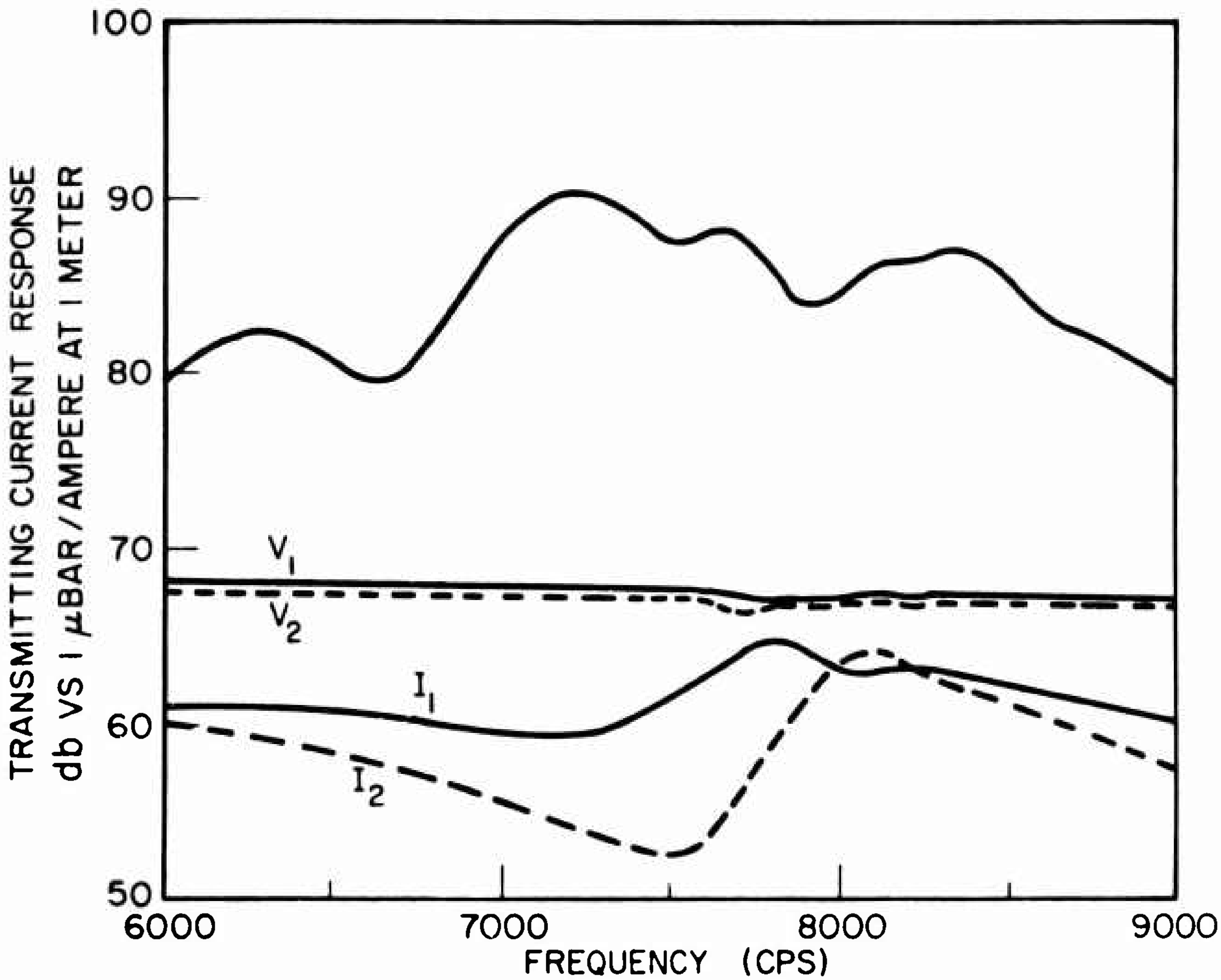

Fig. 17 - Transmitting current response curve
2 line array of magnetostrictive rings
6 series connected rings in each line
Lines driven 90° out-of-phase
Rings = 1-1/2 in. apart
Ring axes = $\lambda/4$ apart

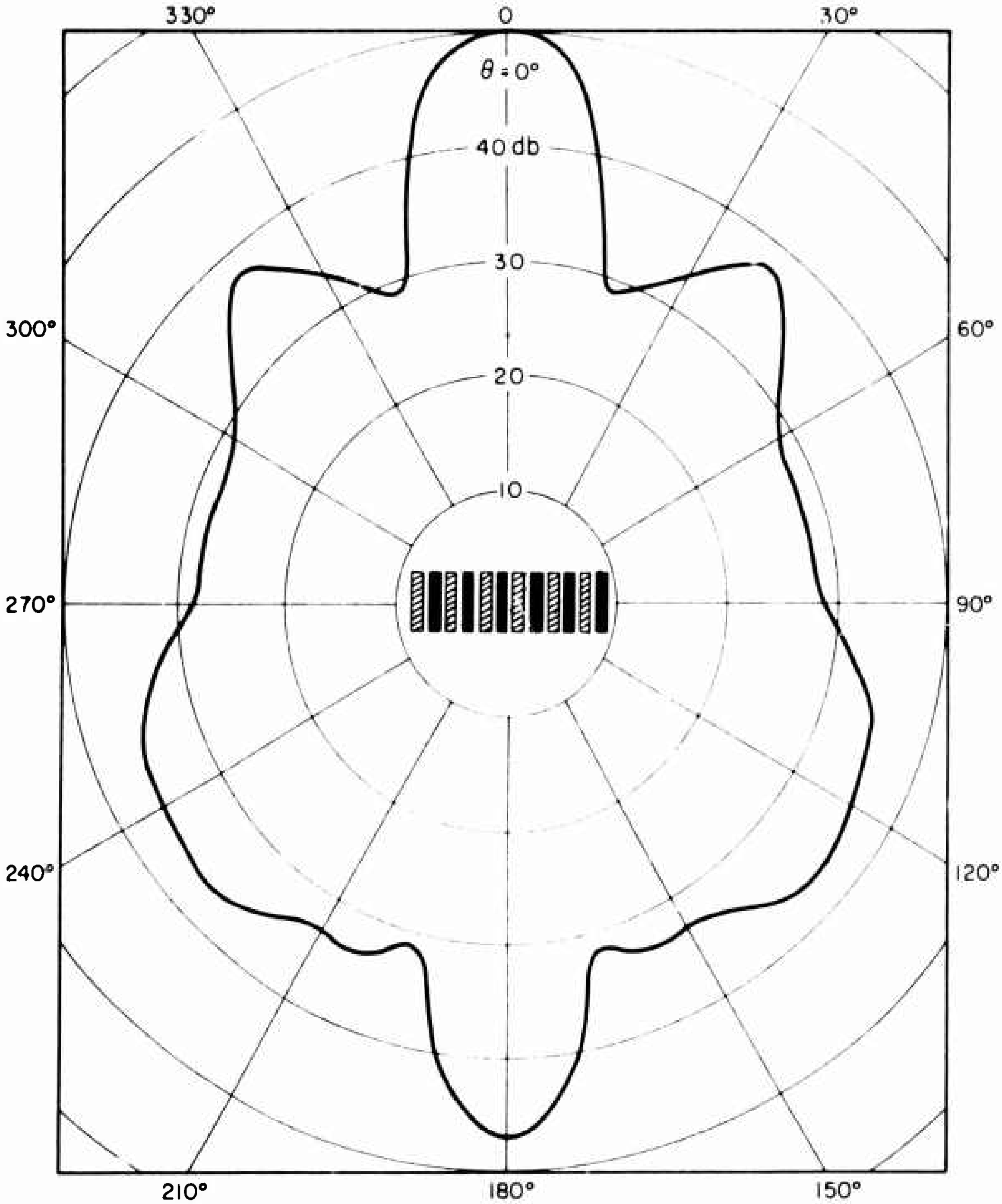

Fig. 18 - Vertical beam pattern
2 line array of rings
Lines driven 90° out-of-phase
Ring axes = $\lambda/4$ apart
Rings = 1-1/2 in. apart
f = 7340 cps

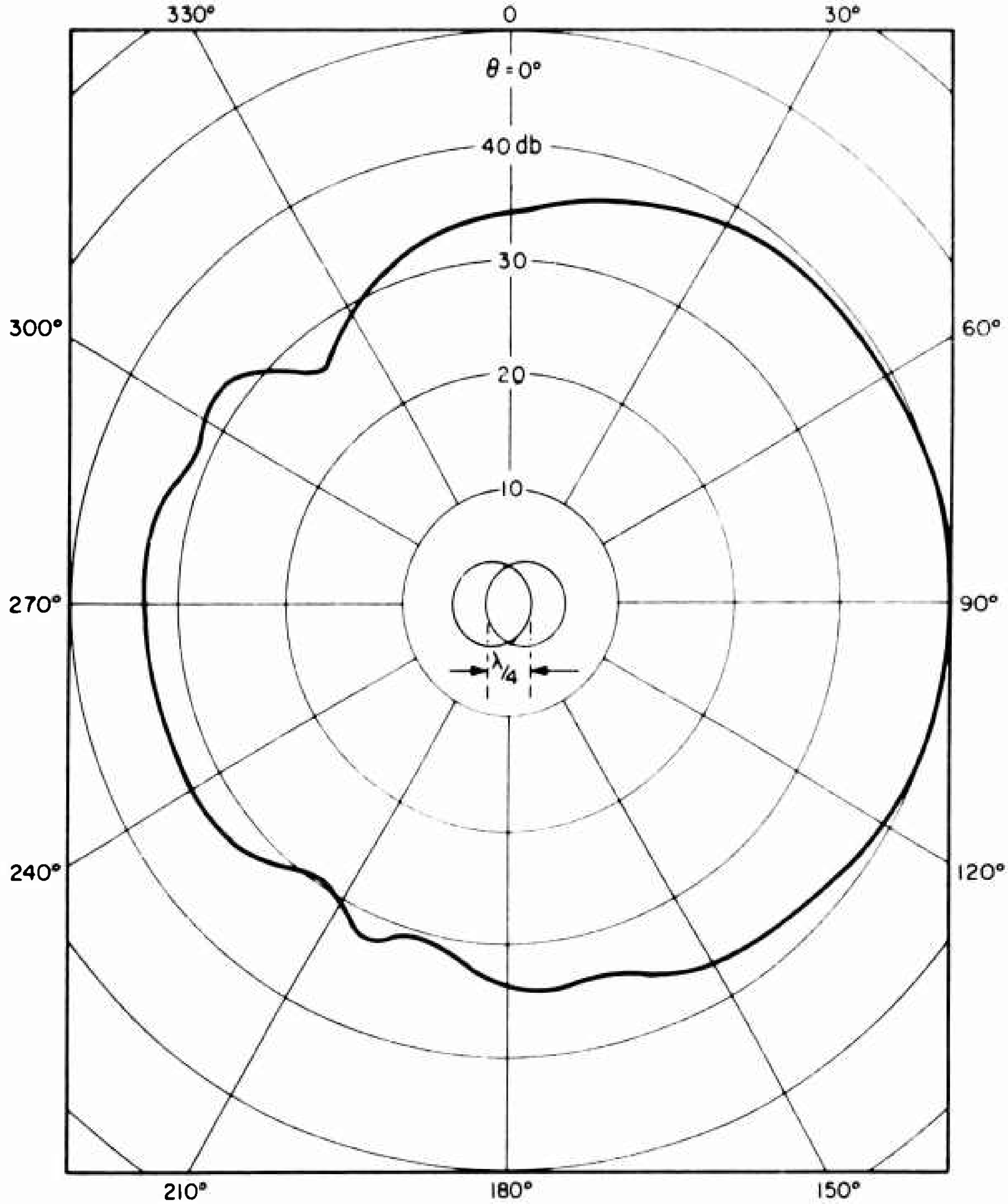

Fig. 19 - Horizontal beam pattern for Fig. 18

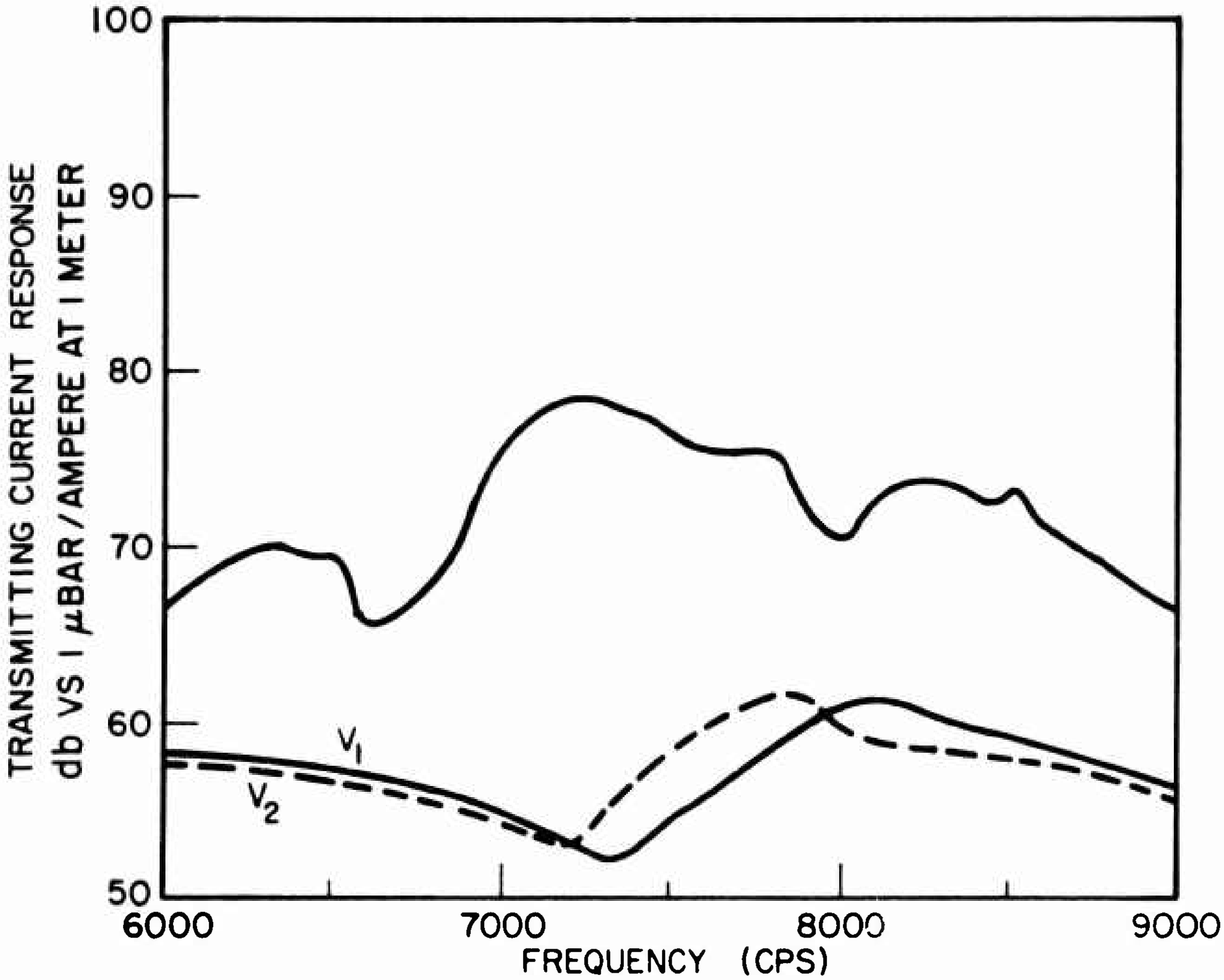

Fig. 20 - Transmitting current response
2 line array of magnetostrictive rings
6 series connected rings in each line
Lines driven 110° out-of-phase
Rings = 1-1/2 in. apart
Ring axes = λ/4 apart

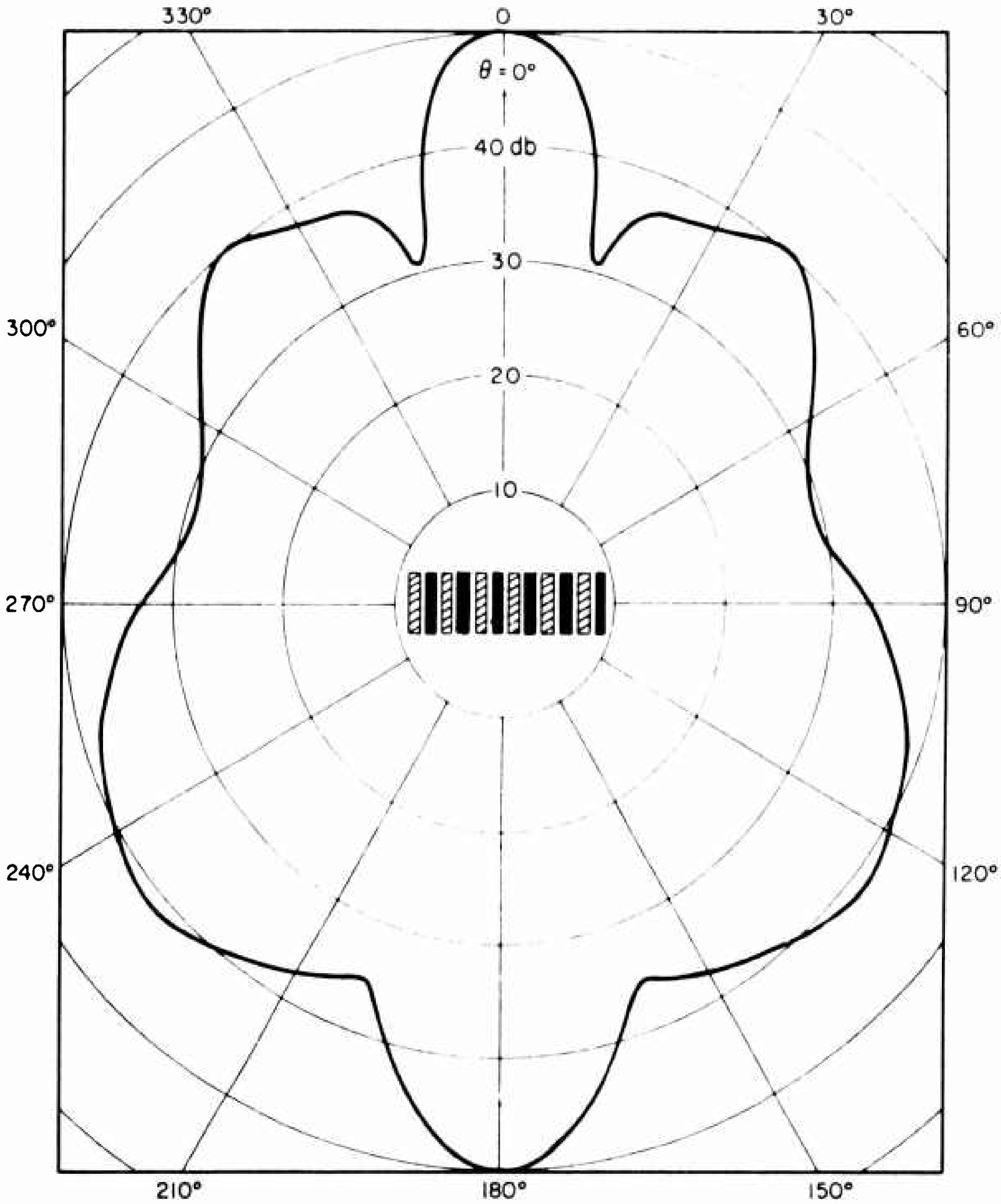

Fig. 21 - Vertical beam pattern
2 line array of rings
Lines driven 110 out-of-phase
Ring axes = $\lambda/4$ apart
Rings = 1-1/2 in. apart
f = 7340 cps

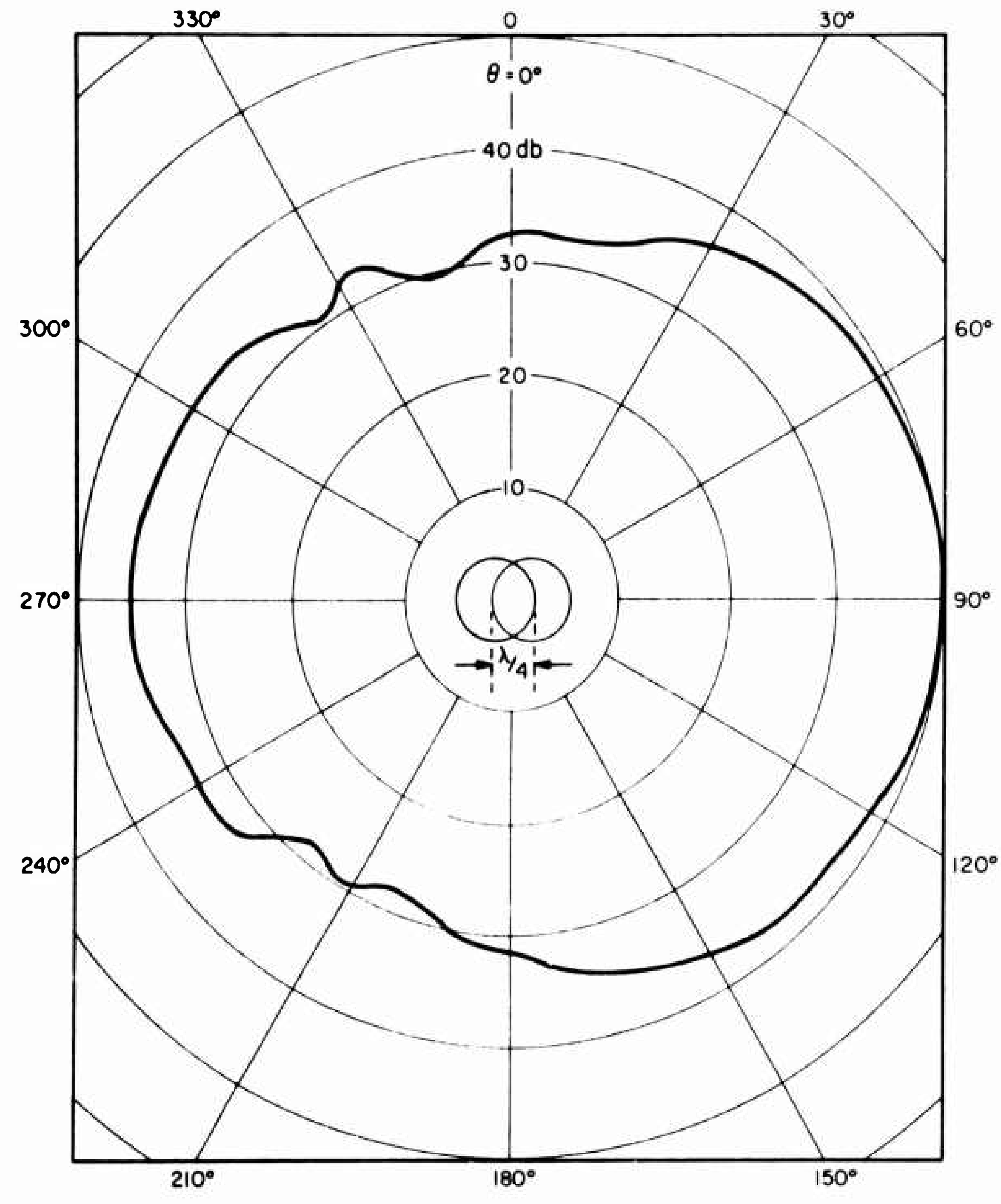

Fig. 22 - Horizontal beam pattern for Fig. 21